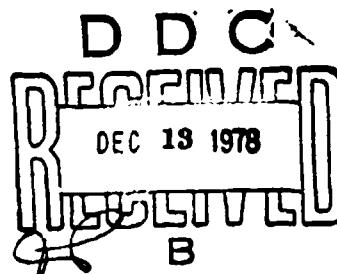AD-E430130

MEMORANDUM REPORT ARBRL-MR-02860

STANDARDIZING THE EVALUATION OF CANDIDATE MATERIALS FOR HIGH L/D PENETRATORS

E. Louis Herr
Chester Grabarek

September 1978

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A procedure using penetration performance criteria for characterizing and evaluating the potential of candidate materials for use as kinetic energy penetrators has been developed.

A preliminary quick method for screening candidate penetrator materials, the up-down V_{50} ballistic limit test and a more complete method of evaluation, the x-ray diagnostic procedure, are described.

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I. INTRODUCTION

The process of armor penetration by a projectile is a very complicated phenomenon. Penetration theory, at least in its present state of development, falls far short of explaining the process. Consequently, the designing of both armor and projectiles has been and continues to be influenced primarily by empirical data from ballistic testing. Although some understanding of the penetration process has been gleaned from analyses of empirical data, a lack of standardization in testing methods, data acquisition, and evaluation criteria and procedures has rendered comparison and interpretation of test results very difficult and has greatly impeded progress toward better understanding of the process.

One of the very important problems in projectile design is evaluation of candidate materials for use as high length-to-diameter (L/D) ratio, i.e., L/D $\geq$ 7, penetrators in large caliber KE projectiles. Considerable ballistic testing is being performed and is contemplated in an attempt to improve understanding of the effect on penetrator performance of changes in material and material properties. It is proposed that the understanding can be achieved more readily and that the results of ballistic testing will be of considerably greater value to the entire ballistics community if test and evaluation procedures are standardized at the several Army, Navy, and Air Force installations interested in this problem and its solution. The BRL procedure for evaluation of candidate penetrator materials which is described below is presented for consideration and adoption as a standard test and evaluation procedure for this purpose. Adoption of the BRL procedure or some other efficient and effective procedure as standard will assure that test results and evaluations performed at different times and places can be compared directly, without the necessity of a painstaking investigation into the effects of differences in testing techniques or evaluation methods, and will have little chance of being misinterpreted.

II. BRL PROCEDURE FOR EVALUATION OF CANDIDATE PENETRATOR MATERIALS

The procedure employed at the BRL for evaluation of candidate penetrator materials consists of three steps: (a) materials processing documentation, (b) materials characteristics documentation, and (c) terminal ballistics testing and data analyses. Each of the three steps is discussed below. Table I presents listings, which are not exhaustive, of the types of materials processing and characteristics which are documented and of the tests which support

Table 1. BRL Procedure for Evaluation of Candidate Penetrator Materials

Materials Documentation[1]		Performance Testing and Analysis
A. Processing	B. Characteristics and Associated Tests	C. Terminal Ballistics

casting
extruding
forging
forming
hardening
 	
heat treatment
annealing
normalizing
quenching
stress relieving
tempering
 	
pressing
sintering
swaging
	1. Physical
	  a. density
	2. Chemical
	  a. qualitative
	  b. quantitative
	3. Mechanical
	  a. defects
	    (1) surface cracks
	    (2) porosity
	  b. hardness
	  c. tensile properties
	    (1) elongation
	    (2) reduction of area
	    (3) stress-strain relationships
	    (4) tensile strength
	    (5) yield strength
	  d. compression properties
	  e. impact properties
	  f. fracture dynamics
	
	4. Associated Tests
	  a. defects tests
	    (1) radiographic
	    (2) ultrasonic
	  b. hardness tests
	  c. tension tests
	    (1) quasi-static
	    (2) dynamic
	    (3) split Hopkinson bar
	    (4) elastomat - longitudinal, transverse torsion
	  d. compression tests
	    (1) quasi-static
	    (2) dynamic
	  e. impact
	    (1) charpy
	    (2) Izod
	  f. fractography
		1. Phase I-Preliminary Section[2,3]
		  a. simple design penetrator(small scale)
		    (1) single-plate target (small scale)
		      (a) ballistic limit velocity, V_{50}, test
		2. Phase II- Secondary Selection[2,3]
		  a. simple design penetrator (small scale)
		    (1) single-plate target (small scale)
		      (a) ballistic limit velocity, V_L, test
		      (b) residual weight, W_R,
		    (2) spaced triple-plate target (small scale) tests as (1) or 2.a.1
		  b. advanced design penetrator (small scale)
		    (1) as a.(1) or 2.a.1
		    (2) as a.(2) or 2.a.2
		3. Phase III - Final Selection
		  a. same as Phase II except that dimensions of penetrators and targets closely approximate those of fielded items

1. Listings are representative but not necessarily exhaustive.
2. Characteristics documentation requirements for this test phase are limited to B.1,2, and 3a, b, and c. Tests B4a, b, and c(1) will supply required mechanical characteristics documentation.
3. Penetrators and targets for this test phase are scaled down considerably from usual dimensions for fielded items.

the characteristics documentation. Table I also presents, in outline, the successive phases of the ballistics testing. It is particularly important that the materials processing and characteristics be documented thoroughly and accurately so that relationships between the materials processing and characteristics and penetrator performance may be investigated, identified, and analyzed.

A. Materials Processing Documentation

This documentation provides basic information on the processes and procedures used in the manufacture of the penetrator. The information includes identification and pertinent details of each process and, especially in the case of penetrators made of new or unusual materials, manufacturer's observations regarding any modification to standard processing or any difficulties encountered in fabricating the penetrator.

B. Materials Characteristics Documentation

This documentation provides quantitative and qualitative information on the physical, chemical, and mechanical characteristics of the penetrator and identifies the tests or types of tests from which certain of these characteristics were obtained. Although only those materials characteristics which are known to have or are strongly suspected of having a significant effect on penetrator performance are documented, the testing required to provide a complete documentation of the characteristics can be both time consuming and expensive. In the BRL procedure for candidate penetrator materials evaluation, required characteristics documentation is very limited, as noted in Table I, unless the penetrator survives the first two phases of terminal ballistics testing and is considered acceptable for the final phase of testing. This limited characteristics documentation may, indeed, eliminate a candidate penetrator without any ballistics testing if, for example, the documentation indicates serious materials defects (see B.3.a. of Table I).

C. Terminal Ballistics Testing and Data Analysis

Currently, fielded, high L/D penetrators for large caliber KE projectiles have masses ranging from approximately 3 to 6 kg and are expected to defeat various conventional armor targets ranging from single-plate, rolled-homogeneous-armor (RHA) configurations with thicknesses of from 100 to 150mm to spaced, multiple-plate configurations of RHA or combinations of RHA and mild steel (MS), e.g., 10mm RHA/330mm space/25mm MS/330mm space/75mm RHA. Such targets generally are expected to present a surface inclined at an obliquity of approximately 60 to 65 degrees to an attacking penetrator.

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The terminal ballistics performance testing and data analyses portion of the BRL procedure for evaluation of candidate penetrator materials consists of three sequential phases: (a) Phase I - Preliminary Selection; (b) Phase II - Secondary Selection; and (c) Final Selection. At the completion of each test phase and at intermediate decision points in Phases II and III the performance data acquired are analyzed by comparing them with previously established standards. The penetrators tested are either rejected from any further consideration or are approved for further testing, if in Phase I, Phase II, or at an intermediate decision point of Phase III, or are recommended for further development, if at completion of Phase III. The penetrator material selected as a standard for ballistic performance comparisons is a tool steel designated as AISI-7. Of course, it is possible to use any penetrator material for which penetrator performance has been established as a basis for comparison.

For test Phases I and II, it is practical, i.e., effective, efficient, and economical, to acquire data by using scaled-down ("small scale") penetrators and targets. These small scale items are similar to fielded items except that their dimensions e.g., mass, length, diameter, thickness, are considerably smaller. Thus, they are cheaper, easier to handle, and they do not require test range facilities and equipment of the size needed for testing the fielded items. Previous experience in ballistic testing of various sizes of penetrators led to selection of standard dimensions and shape for the "simple-design" penetrator used in test Phase I and the first part of test Phase II (see Table I and text below) as follows:

       mass - 65 grams,
       L/D   - 10,
       shape - truncated right cylinder with hemispherical nose.

The simple design penetrator is illustrated in Figure 1 together with the two-piece carrier or sabot, steel disc, and pusher plug used in firing the penetrator.

The small scale targets used in test Phases I and II are scaled according to the target plate thickness-to-penetrator diameter (T/D) ratio for fielded, high L/D penetrators and the conventional single-plate targets they are expected to defeat. The T/D ratio value under these conditions ranges from 2.0 to 4.0. To maintain this range of values for the small-scale testing, the small-scale, single-plate target is defined to be 25.4mm RHA/60° obliquity. The T/D ratio value for this target and a small-scale, simple-design, steel penetrator is 2.5 and for a similar, high-density penetrator is 3.3. The small-scale,
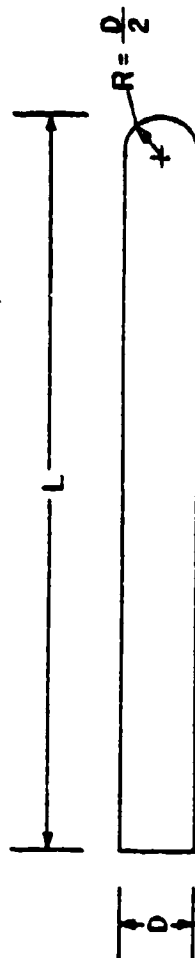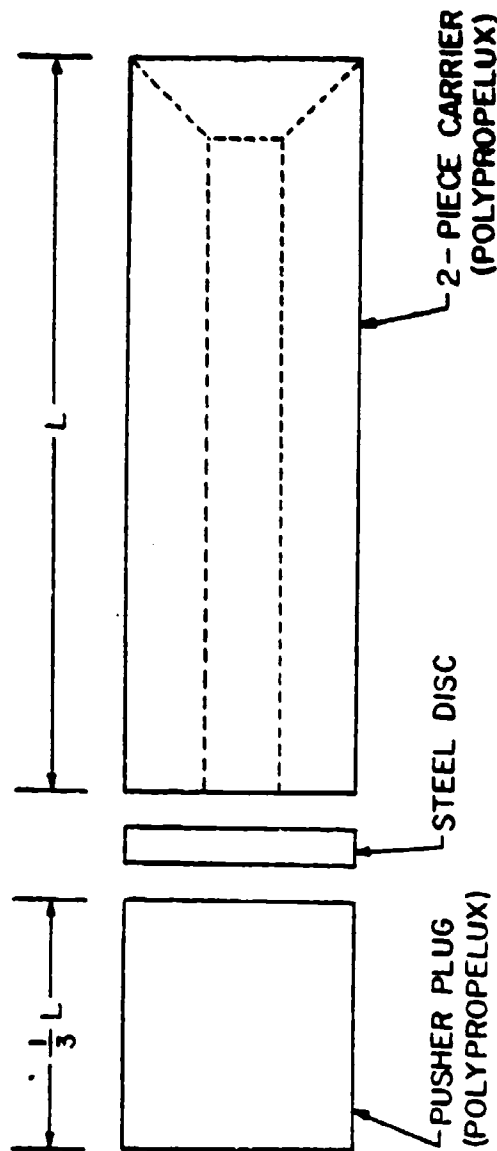
Figure 1. Penetrator (simple design) and Firing Accessories

spaced, triple-plate target is defined to be 2.39mm PHA/83mm space/ 6.35mm MS/83mm spaced/12.7mm RHA/65° obliquity. Figures 2 and 3, respectively, illustrate the single-plate and spaced, triple-plate targets and the placement of flash x-ray equipment[1] used for experimental data acquisition. Details of the three phases of terminal ballistic testing are discussed below.

1. Phase I - Preliminary Selection

In this test phase, simple-design, small-scale penetrators fabricated from the material being evaluated are fired against the small-scale single-plate target in order to determine the V_{50} ballistic limit velocity, i.e., the striking velocity V_S at which the probabilities of complete and partial penetration of the target are equal, for the penetrator. The V_{50} value for the penetrator being tested is then compared with the previously established V_{50} value for the standard penetrator under the same (small-scale) test conditions to determine whether the penetrator fabricated from the new material should be tested further. The effect of penetrator material on performance, as is the case in each test phase, is the basis for decision since the targets are identical and the penetrator characteristics of the penetrator being tested and the standard penetrator are identical except for material. Table II illustrates the use of the evaluation criterion, the ratio of V_{50} values for new-material and standard-material penetrators, and the selection disposition for the test phase.

Table II. Preliminary Selection Phase Disposition

Criterion $V_{50}{}^{a}/V_{50}{}^{b}$	Rating	Disposition
<1.05	favorable	Proceed to Phase II testing
≥1.05	unfavorable	Discontinue testing; store data for future reference

[a] new material penetrator

[b] standard material penetrator

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[1] C. Grabarek and E. L. Herr, "X-Ray M s System for Measurement of Projectile Performance at the Target" ic Research Laboratories Technical Note No. 1634, September 1 ?619).
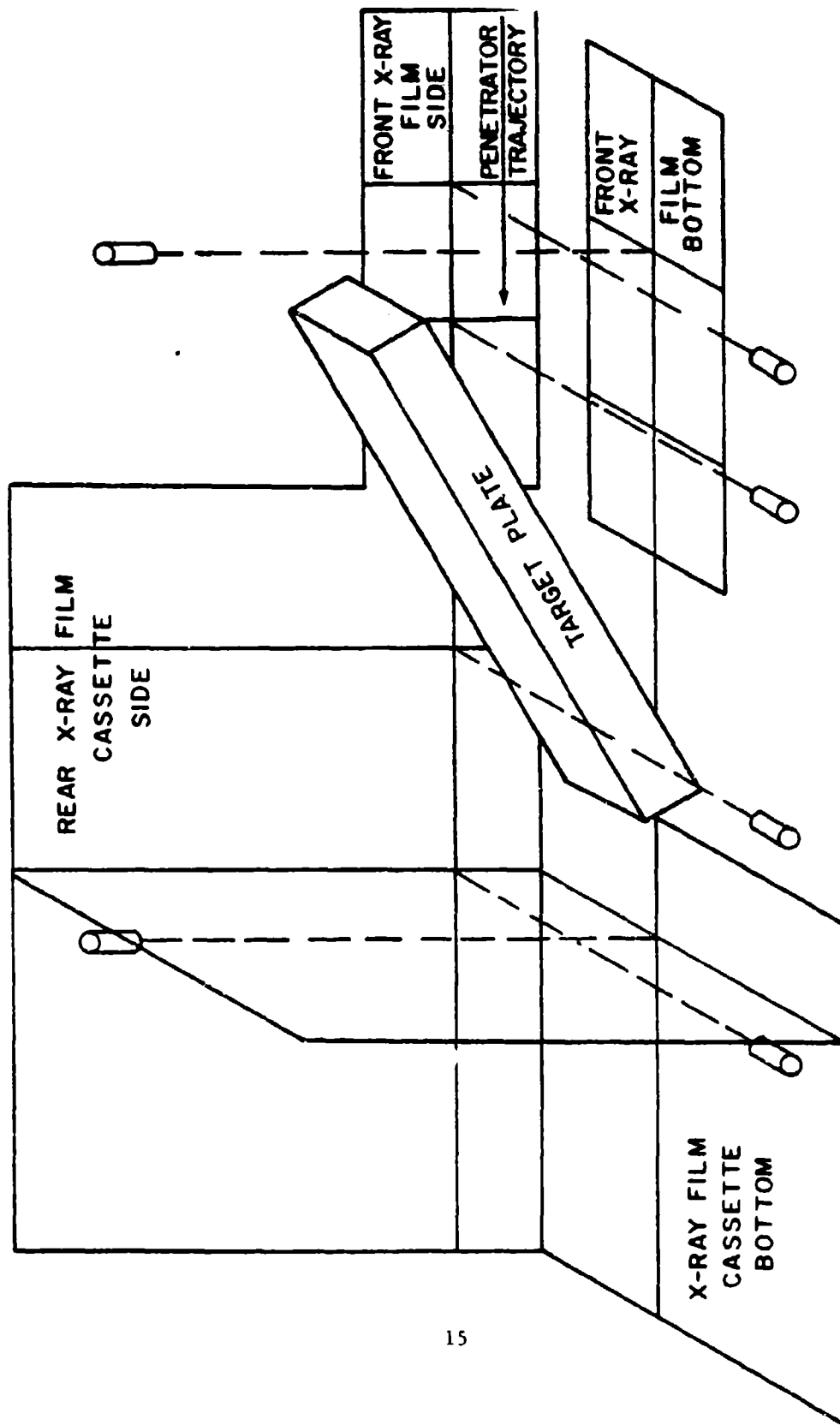
Figure 2. Diagram of Experimental Setup for Single Plate Tests
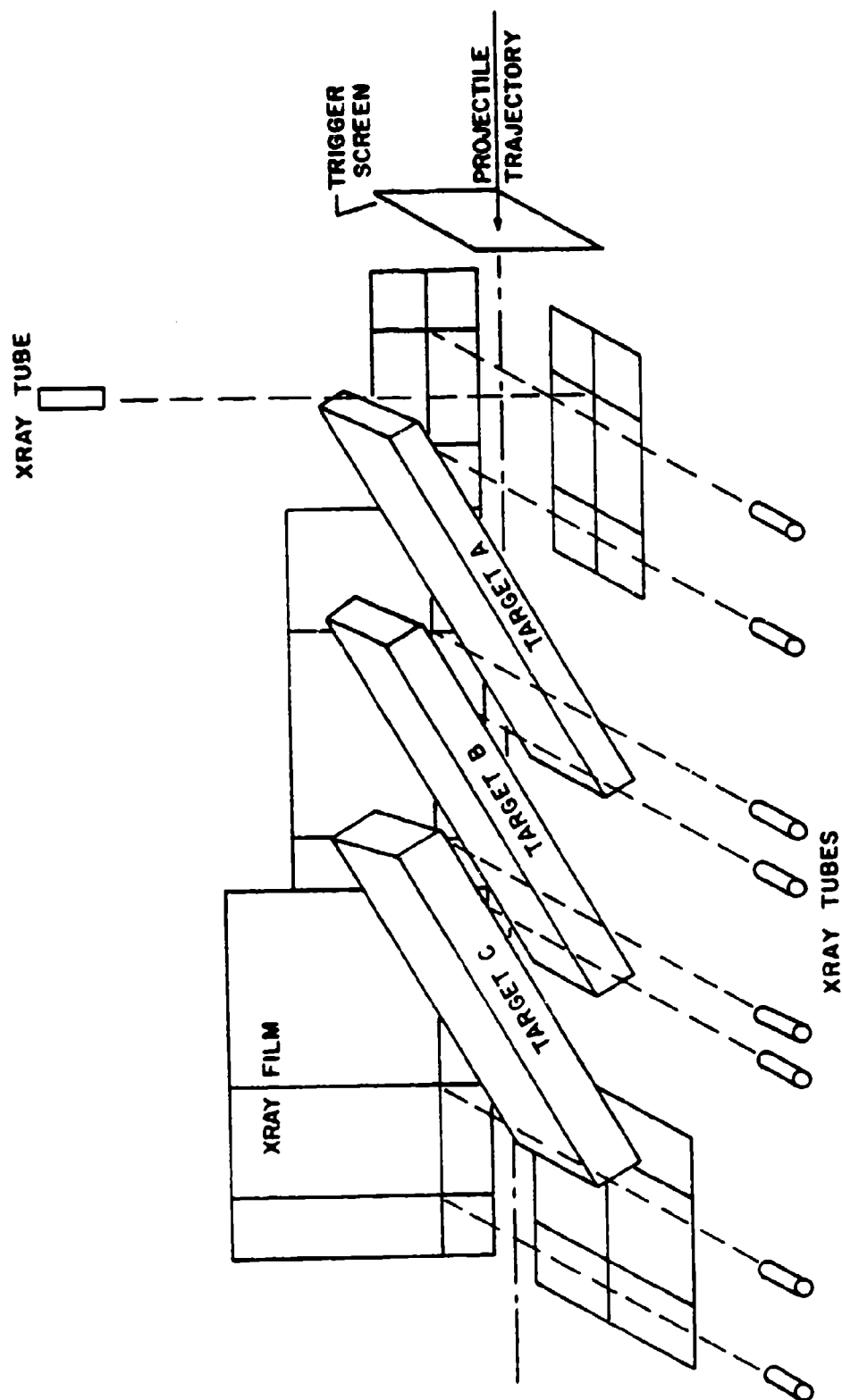
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Figure 3. Diagram of Experimental Setup for Spaced Plate Tests

The data acquisition and analysis procedure used to determine the value of V_{50} for the penetrator being tested is referred to as the "up-down" method. In order to determine a value of V_{50}, the up-down method requires an estimate of the ballistic limit velocity, V_L, for the penetrator being tested and an estimate of the spread, σ of the striking velocity interval associated with probabilities of complete penetration which are greater than zero but less than one.

V_L is the greatest lower bound of values of striking velocity which are associated with consistent complete penetration of a target, and the required estimate, V_L^*, is obtained from

$$(V_L^*) = \frac{AD^\gamma \left[T(\sec \theta)/D \right]^\alpha}{M} , \qquad (1)$$

where:

V_L^* = estimated value of ballistic limit velocity, V_L, m/s
T = target plate thickness, mm
D = penetrator diameter, mm
M = penetrator mass, grams
A, γ, α = computational coefficients dependent on values which may be found in Reference 2
θ = target obliquity angle

The derivation of Equation (1) is discussed in Reference 3. The estimate of σ for the up-down procedure is arbitrarily set at $\sigma = 40$ m/s.

The firing procedure for the determination of $V_{(50)}$ is as follows:

1.1 <u>Striking velocity for first round</u>

$$V_1 = V_L \qquad (2)$$

1.2 <u>Striking velocity for second round</u>

a. If the first round is a complete penetration the strike velocity is

$$V_2 = V_1 - (1/2) \sigma \qquad (3)$$

[2] Chester L. Grabarek, "An Armor Penetration Predictive Scheme for Small Arms AP Ammunition (U)", Ballistic Research Laboratories Memorandum Report No. 2620, April 1976 (CONFIDENTIAL). (AD #C006096L)
[3] C. L. Grabarek, "Penetration of Armor by Steel and High Density Penetrators (U)", Ballistic Research Laboratories Memorandum Report No. 2134, October 1971 (CONFIDENTIAL). (AD #518394L)

b. If the first round is a partial penetration the strike velocity is

$$V_2 = V_1 + (1/2) \sigma \qquad (4)$$

1.3 Striking velocity for third round

a. If the first two rounds give a reversal in the order of a complete penetration and a partial penetration, the strike velocity for the third round is

$$V_3 = V_2 + (1/2) \sigma \qquad (5)$$

b. If the first two rounds give a reversal in the order of a partial penetration and a complete penetration the strike velocity for the third round is

$$V_3 = V_2 - (1/2) \sigma \qquad (6)$$

c. If the first two rounds give either two complete penetrations or two partial penetrations the strike velocity for third round is

$$V_3 = V_2 \pm (1/2) \sigma \qquad (7)$$

The plus sign is used when there were two partial penetrations and the minus sign is used when there were two complete penetrations.

1.4 Striking velocity for succeeding rounds

a. Where a reversal was obtained, refer to steps in sub-paragraphs 3a and b, fire five more rounds where the strike velocity for each round is either raised (for a partial) or lowered (for a complete) by an amount equal to $(1/2) \sigma$.

b. If the steps in sub-paragraph 3c did not produce a reversal continue using the procedure in 3c until a reversal is obtained. Then use firing procedure as described in paragraph 4a.

1.5 Analysis of results

a. If the test firings do not produce a zone of mixed results, i.e., of partial and complete penetration, over a relatively narrow V_S interval, a V_{50} value is determined by mathematically averaging the highest striking velocity which resulted in a partial penetration and the lowest striking velocity which resulted in a complete penetration.

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b. If the test firings do produce a zone of mixed results over a relatively narrow V_S interval, a V_{50} value is calculated by assuming a normal distribution of probability of complete penetration over the interval and applying the method of maximum likelihood for the associated cummulative distribution[4]. The calculations are either carried out by using the computer program in the Appendix, or a value of V_{50} is obtained by graphical techniques.

2. Phase II - Secondary Selection

In this test phase there are four steps in which small-scale penetrators fabricated from the material being evaluated are fired against small-scale targets to determine whether penetration performance warrants further testing. Elimination of the penetrators being tested from further consideration may occur as a result of analyses of test data acquired in any one of the four steps which are:

a. firings of simple-design penetrators against
   (1) the single-plate target and
   (2) the spaced, triple-plate target, and

b. firings of advanced-design penetrators* against
   (1) the single-plate target and
   (2) the spaced, triple-plate target

There are two criteria which are used jointly for performance evaluation in this test phase: (1) the ratio of V_L values for the new-material and standard-material penetrators and (2) the ratio of the residual mass, M_R, to the striking mass, M_S, of the new-material penetrator. The striking mass, M_S, of a penetrator is the mass at the instant of impact on the target, and the residual mass, M_R, is mass of the portion (or of the largest portion, in case of break up) of the penetrator which exits from the rear face of the target. Table III illustrates the use of the evaluation criteria and the selection disposition applicable to each step in test Phase II and test Phase III, which is described later.

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[4]A. Golub and F. Grubbs, "Analysis of Sensitivity Experiments When the Levels of Stimulus Cannot be Controlled", American Statistical Journal, June 1956.

*Advanced-design penetrators have the same mass and L/D or the simple-design, small-scale penetrators, but they also have design features such as: subcaliber or supercaliber threads to provide for mating with threaded sabots, armor piercing nose cap to improve penetration capability, or sheaths (in the case of high-density-material penetrators).

Table III. Secondary and Final Phase Disposition

Criteria				
V_L^a/V_L^b	$M_R^{a,c}/M_S^a$	Residual Penetrator[a] Breakup	Rating	Disposition
<1.05	≥0.05	none to moderate	favorable	proceed with testing[d]
≥1.00	<0.05	moderate to heavy	unfavorable	discontinue testing; store data

[a] for new-material penetrator
[b] for standard-material penetrator
[c] for striking velocity, V_S, within 3% of V_L

[d] proceed to next step of test phase, to next test phase, or recommend penetrator for further development of all test phases completed.

The data acquisition and analysis procedures for determination of a V_L value and an associated M_R for a striking velocity, V_S, within 3% of V_L) for the penetrator being tested are as follows. The V_L value for the penetrator-target combination of interest is obtained through mathematical analysis of residual velocity, V_R, data from a series of N (N<8) acceptable test firings of the penetrator against the target. In order to be considered acceptable for this test purpose, a round may not have an impact yaw greater than two degrees. The N rounds are fired sequentially with striking velocity, $V_{S(i)}$, for the i-th (i=1,2,...,N) round decreased systematically from an initial maximum value of V_S, usually considerably above the estimated ballistic limit velocity, V_L^*, obtained from Equation (1), by decreasing the propellant charge for each subsequent round fired.

$$V_{S(i)} = \begin{cases} f\, V_{M(max)} & , \quad i=1 \\ V_L^* + (1/3)\left(V_{S(i-1)} - V_L^*\right) & i>1 \end{cases} \tag{8}$$

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where:

$V_{S(i)}$ = V_S for the i-th test round fired.

$V_{M(max)}$ = the maximum, safe muzzle velocity, V_M, for the projectile (penetrator and sabot) and gun being used in the tests.

$V(V_{M(max)})$ = the striking velocity for the initial round, i=1, of the test series. Since the distance from gun muzzle to target is very short on the test ranges, V_{si} for the initial round will be a close approximation to $V_{M(max)}$

V_L^* = estimated value of V_L or previously defined.

Values of the residual velocity, V_R, and mass, M_R, (the velocity and mass of the portion, or of the largest portion in case of breakup, of the penetrator which exits from the rear face of the target) are determined for each acceptable round fired by reduction of flash radiographic data such as shown in Figure 4, acquired during the test firings. At least two values of V_R associated with different values of V_S are required for mathematical determination of V_L using the method described below in this section.

The procedure for V_R data acquisition and analysis is as follows:

2.1 If:

    a. N=6 acceptable rounds have been fired and
    b. V_R > 100 m/s for each round,

  then:

    a. testing is discontinued,
    b. the V_R data are analyzed to obtain a value of V_L, and
    c. one additional round is fired with a charge such that $V_{S(N+1)}$ = V_L in order to verify the calculated value of V_L.

2.2 If:

    a. $2 \leq N \leq 6$ acceptable rounds have been fired,
    b. V_R > 0 m/s for at least two rounds, and
    c. 0 m/s < $V_R \leq$ 100 m/s for one round,

  then:

    a. testing is discontinued, and
    b. the V_R data are analyzed to obtain a value of V_L.

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Figure 4. Flash Radiograph of a 65 Gram Rod (L/D – 10) Perforating a Small Scale, Spaced Triple Plate Target

2.3 If:

    a. $3 \leq N \leq 6$ acceptable rounds have been fired,

    b. $V_R > 100$ m/s for all rounds except the last one fired, and

    c. $V_R = 0$ m/s for the last round fired, i.e., for the N-th round,

then:

    a. fire an additional round, the N + 1st round, such that $V_{S(N+1)} = V_L + (2/3)\,(V_{S(N-1)} - V_L{}^*)$ and

    b. if 0 m/s $< V_R \leq 100$ m/s for the N+1 round, discontinue testing and analyze all V_R data acquired to obtain a value of V_L <u>or</u>

    c. if $V_R = 0$ for the N+1st round, fire one more round, the N+2nd round, such that and $V_{S(N+2)} = V_{S(N-3)}$

    d. regardless of the value of V_R for the N+2nd round, discontinue testing and analyze all V_R data to obtain a value of V_L.

The mathematical analysis of the experimental V_R data which produces the value of V_L for the penetrator-target combination of interest consists of making a "best fit" of the following mathematical model to a set of V_R data:

$$V_R = \begin{cases} 0 & , \ 0 \leq V_S \leq V_L \\[2ex] a(V_S{}^p - V_L{}^p)^{1/p} & , \ V_S > V_L \end{cases} \qquad (9)$$

with constraints $0 \leq a \leq 1$ and $p > 1$ and

where:

    V_R, V_S, V_L are as previously defined

    a, p, V_L are paramaters whose values are adjusted to provide the best fit of the model to the data.

The model; a direct, nonlinear, least-square algorithm for fitting the model to sets of experimentally obtained V_R data; and a computer program for generating V_R versus V_S curves were all developed recently at the Terminal Ballistics Division, TBD, of the BRL[5]. Figure 5 presents a typical, computer-generated V_R versus V_S curve and identifies the values of a, p, and V_L obtained from fitting the mathematical model to a set of experimental data. The test-firing procedure for determining values of V_R, i.e., Equation (9), tends to provide good definition of the portion of the curve having maximum curvature and, consequently, an accurate determination of the V_L value.

3. Phase III - Final Selection

In this test phase, there are four steps which are identical with those outlined above for Phase II except that the dimensions of the penetrators and of the armor targets used in Phase III closely approximate those of fielded items. Consequently, the standard dimensions and shape for the simple-design penetrator in this phase are:

> mass - 4.2 kg,
> L/D - 10,
> shape - truncated right cylinder with hemispherical nose.

The advanced-design penetrator has the same mass and L/D as the simple-design penetrator, but it also has design features such as noted for the small-scale, advanced-design penetrators (see page 19). The single-plate target for this phase is defined to be 102mm RHA/60° obliquity, and the spaced, triple-plate target is defined to be 9.5mm RHA/330mm space/25.4mm MS/330mm space/76.2mm RHA.

The criteria for performance evaluation in this test phase and the data acquisition and analysis procedures for determination of a V_L value and associated M_R value for the penetrator being tested are identical with the criteria and procedures described in the Phase II discussion above. Table III, as noted previously, illustrates the use of the evaluation criteria and the selection disposition for this test phase.

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[5]*J. P. Lambert and G. H. Jonas, "Towards Standardization in Terminal Ballistics Testing: Velocity Representation", Ballistic Research Laboratories Report No. 1852, January 1976. (AD #A021389)*
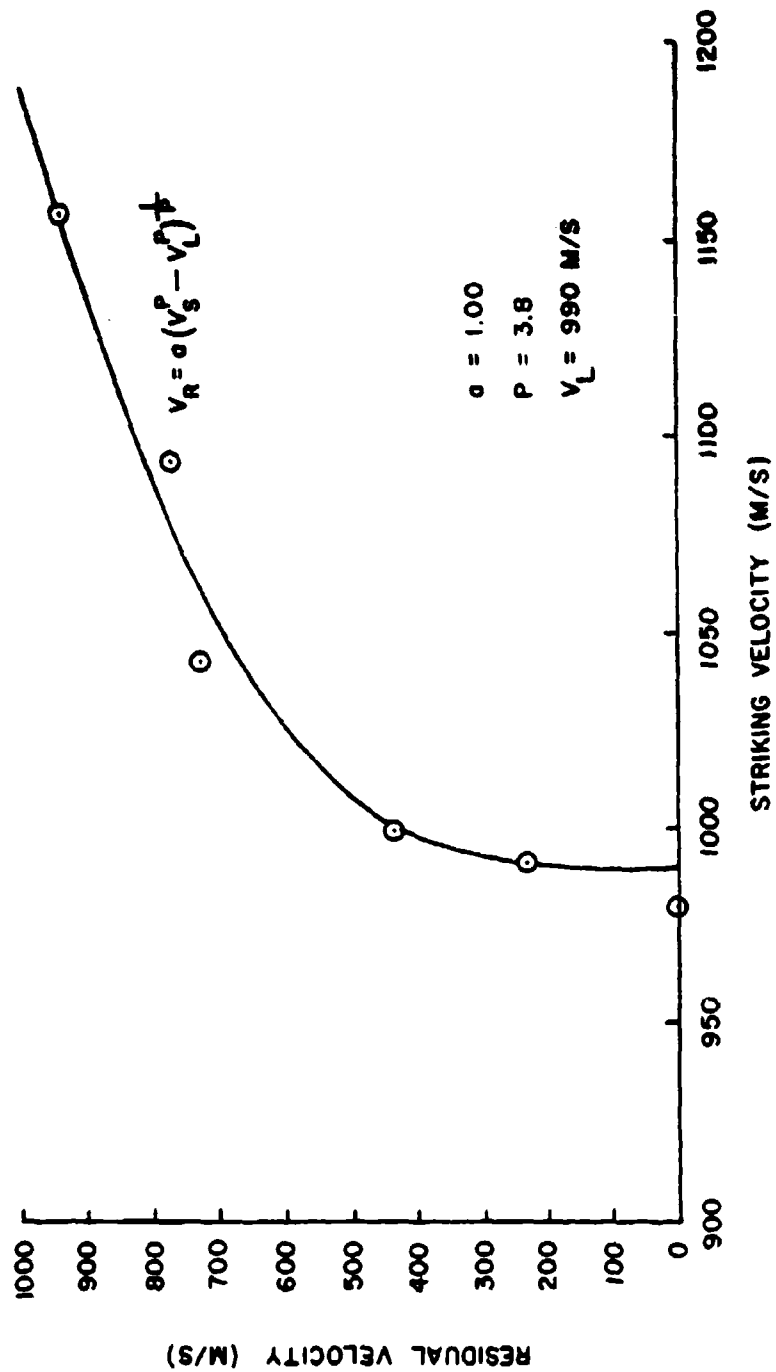
Figure 5. Residual Velocity as a Function of Striking Velocity for 65 Gram Rod (L/D – 10) Perforating a Small Scale, Single Plate Target

III. CONCLUSION

This report is intended to provoke serious consideration of the problems involved in the evaluation of candidate materials for high L/D penetrators and, especially, of the need for standardization of evaluation procedures, e.g., laboratory and field testing conditions, data acquisition and analysis techniques, and evaluation criteria definition and application. The BRL has had reasonable success in applying the evaluation procedure described here and strongly recommends adoption of this procedure or of some other effective and efficient procedure as a standard for use in penetrator candidate material evaluation. As noted, such standardization should benefit all interested organizations since it will facilitate interchange of test data and evaluation information and eliminate the possibility of misinterpretation of shared information. The common approach to solution of the evaluation problem should improve basic understanding of the penetration process and promote problem solution.

APPENDIX A

COMPUTER PROGRAM FOR METHOD OF MAXIMUM LIKELIHOOD

```
        LIST(START)
$       MAXO(5000)LINES
$       MAXT(5)MINUTES
C       MAX LIKELIHOOD EST OF MEAN AND STD DEV FOR SENSITIVITY TESTING
C       FOLLOWING A NORMAL DISTRIBUTION
C       AGVES KODAT
C       JUNE 69
        DIMENSION S(500),X(500),T(500),Z(500),P(500),ZETA(500),
       1PHI(500),GAMMA(500),PSI(500),TAU(500),ALPHA(500),BETA(500),
       2DELTA(500),SS(100),K(100),MX(100),ZP(8),ST(12),SDP(12),S9L(12),
       3S9U(12),S8L(12),S8U(12),RR(100),XM(50),KK(50),SSL(100),STI(500)
1000    FORMAT (A10)
1050    FORMAT(3I2)
1060    FORMAT(I4/(F8.0,2I4))
1070    FORMAT('1'///T5,
       1'MAX LIKELIHOOD EST OF MEAN AND STD DEV FOR SENSITIVITY TESTING'/
       2T20,'FOR GROUPED DATA')
1080    FORMAT(2F6.0)
1090    FORMAT(///T5,'NO ZMR')
2000    FORMAT(I4/(F8.0,F4.0))
2010    FORMAT('1'///T5,
       1'MAX LIKELIHOOD EST OF MEAN AND STD DEV FOR SENSITIVITY TESTING'
       2/T5,'FOLLOWING A NORMAL DISTRIBUTION'/T5,
       3'UNGROUPED DATA-ZONE OF MIXED RESULTS',30X,'WEAPON-TARGET',3X,A4)
2015    FORMAT(///T5,'ITERATION'//T14,'MEAN',T54,'STD.DEV.')
2020    FORMAT(I4,4E20.8)
2030    FORMAT(///T5,'EST.MEAN     =',F20.7/T5,'EST.SIGMA    =',F20.7/T5,
       1'VAR(MEAN)    =',E20.7/T5,'VAR(SIGMA)   =',E20.7/T5,'COVARIANCE  =',
       2E20.7/T5,'DETERMINANT =',E20.7/T5,'NO. OF SAMPLE POINTS =',I8)
2040    FORMAT(///T29,'90 PER CENT',T53,'80 PER CENT'/T3,'PROB.',T12,
       1'STIMULUS',T27,'CONF. INTERVAL',T51,'CONF. INTERVAL'//T4,'.005',
       25F12.3/T4,'.01 ',5F12.3/T4,'.05 ',5F12.3/T4,'.10 ',5F12.3/
       3T4,'.25 ',5F12.3/T4,'.50 ',5F12.3/T4,'.75 ',5F12.3/T4,'.90 ',
       45F12.3/T4,'.95 ',5F12.3/T4,'.99 ',5F12.3/T4,'.995',5F12.3)
2045    FORMAT('1',T5,'INPUT'//)
2055    FORMAT(T5,'STIMULUS',T18,'RESULT'//)
2065    FORMAT(F12.3,F9.0)
2070    FORMAT(//(F10.3,5F12.4))
2075    FORMAT('1'///T5,'INPUT'//T5,'STIMULUS',T19,'LN(ST)',T31,'RESULT'//
       1)
2080    FORMAT(F12.3,F12.4,F9.0)
2090    FORMAT('1'///T5,'INPUT'//T5,'STIMULUS',T17,'NO. OF TRIALS',T34,
       1'NO. OF RESPONSES',T54,'RESPONSE RATE'//(F12.4,7X,I8,10X,I8,10X,
       2F8.4))
2095    FORMAT('1'///T5,'INPUT'//T5,'STIMULUS',T19,'LN(ST)',T29,'NO. OF TR
       11ALS',T46,'NO. OF  RESPONSES',T66,'RESPONSE RATE'//)
3000    FORMAT(I12.3,F12.4,7X,I8,10X,I8,10X,F8.4)
3       READ (5,1000) WEAP
        READ(5,1050)ICODE,NG,LG
        IF(ICODE-98)4,450,450
4       GO TO(40,101,ICODE
10      READ(5,1060)NN,(SS(J),K(J),MX(J),J=1,NN)
        WRITE(5,1070)
        WRITE(5,2015)
        L=0
        DO 30 J=1,NN
        MM=MX(J)
        KM=K(J)-MX(J)
```

```fortran
        IF(MM)21,21,23
21      DO 22 JJ=1,KM
        S(L+JJ)=SS(J)
        X(L+JJ)=0.
22      CONTINUE
        L=L+KM
        GO TO 30
23      IF(KM)26,26,24
24      DO 25 JK=1,KM
        S(L+JK)=SS(J)
        X(L+JK)=0.
25      CONTINUE
        L=L+KM
26      DO 27 JL=1,MM
        S(L+JL)=SS(J)
        X(L+JL)=1.
27      CONTINUE
        L=L+MM
30      CONTINUE
        N=L
        GO TO 42
40      READ(5,2000)N,(S(I),X(I),I=1,N)
        WRITE(5,2010) MEAP
        WRITE(5,2015)
42      IF(LG .EQ. 1)GO TO 45
        GO TO 50
45      DO 46 I=1,N
        ST(I)=S(I)
        S(I)=DLOG(S(I))
46      CONTINUE
50      ITER=0
        IF(MG .EQ. 1)GO TO 80
        BIGA=0.
        SMALL=9999.
        DO 58 I=1,N
        IF(X(I))55,52,55
52      IF(S(I)-BIGA)58,58,53
53      BIGA=S(I)
        GO TO 58
55      IF(S(I)-SMALL)56,58,58
56      SMALL=S(I)
58      CONTINUE
        IF(BIGA .LE. SMALL)GO TO 90
        TN=N
        M=0
        ZM=0.0
        DO 70 I=1,N
        IF(SMALL-S(I))60,60,70
60      IF(S(I)-BIGA)65,65,70
65      ZM=ZM+S(I)
        M=M+1
        DIV=M
70      CONTINUE
        AMU=ZM/DIV
        SIGMA=(BIGA-SMALL)*DEXP(-.07D0-.0135D0*TN)
        GO TO 100
80      READ(5,1080)AMU,SIGMA
        GO TO 100
90      WRITE(5,1090)
        GO TO (410,420),ICODE
```

```
100    DO 110 I=1,N
110    T(I)=(S(I)-AMU)/SIGMA
       CALL PROB(N,T,Z,P)
       F=0.0
       G=0.0
       A=0.0
       B=0.0
       D=0.0
       RHO=1./SIGMA
       Q=RHO*RHO
       DO 200 I=1,N
       ZETA(I)=Z(I)/(P(I)*(1.-P(I)))
       PSI(I)=(1.-P(I))*X(I)+(P(I)-X(I))*P(I)
       TAU(I)=(T(I)*T(I)-1.)*(P(I)-X(I))-T(I)*ZETA(I)*PSI(I)
       PHI(I)=ZETA(I)*RHO*(P(I)-X(I))
140    F=F+PHI(I)
       GAMMA(I)=PHI(I)*T(I)
150    G=G+GAMMA(I)
       ALPHA(I)=RHO*(GAMMA(I)-RHO*ZETA(I)*ZETA(I)*PSI(I))
160    A=A+ALPHA(I)
       BETA(I)=RHO*RHO*ZETA(I)*TAU(I)
170    B=B+BETA(I)
       DELTA(I)=Q*(T(I)*ZETA(I)*TAU(I)-T(I)*ZETA(I)*(P(I)-X(I)))
180    D=D+DELTA(I)
200    CONTINUE
       Y2=(-G+(B*F)/A)/(D-(B*B)/A)
       Y1=-F/A-(B/A)*Y2
       WRITE(5,2020)ITER,AMU,Y1,SIGMA,Y2
       ITER=ITER+1
       IF(ITER-25)205,3,205
205    IF(DABS(Y2)-.001)210,210,220
210    IF(DABS(Y1)-.001)230,230,220
220    IF(Y1+SIGMA)221,221,222
221    AMU=AMU-SIGMA
       GO TO 225
222    IF(Y1-SIGMA)223,224,224
223    AMU=AMU+Y1
       GO TO 225
224    AMU=AMU+SIGMA
225    IF(Y2+SIGMA/2.)226,226,227
226    SIGMA=SIGMA/2.
       GO TO 100
227    IF(Y2-SIGMA)228,229,229
228    SIGMA=SIGMA+Y2
       GO TO 100
229    SIGMA=2.*SIGMA
       GO TO 100
230    AMU=AMU+Y1
       SIGMA=SIGMA+Y2
       DO 235 I=1,N
235    T(I)=(S(I)-AMU)/SIGMA
       CALL PROB(N,T,Z,P)
       AA=0.0
       AB=0.0
       BB=0.0
       DO 240 I=1,N
       AA=AA+(Z(I)*Z(I))/(P(I)*(1.-P(I))*SIGMA*SIGMA)
       AB=AB+(Z(I)*Z(I)*T(I))/(P(I)*(1.-P(I))*SIGMA*SIGMA)
       BB=BB+(Z(I)*Z(I)*T(I)*T(I))/(P(I)*(1.-P(I))*SIGMA*SIGMA)
240    CONTINUE
```

```
      XI=AA*BB-AB*AB
      VARMU=BB/XI
      VARSIG=AA/XI
      COVAR=-AB/XI
      WRITE (5,203))AMU,SIGMA,VARMU,VARSIG,COVAR,XI,N
      ZP(1)=2.57583
      ZP(2)=2.32635
      ZP(3)=1.64485
      ZP(4)=1.28155
      ZP(5)=).67449
      ZP(6)=0.0
      DO 250 I=1,6
      ST(I)=AMU-ZP(I)*SIGMA
      SDP(I)=DSQRT(VARMU+VARSIG*ZP(I)**2-2.D0*ZP(I)*COVAR)
      S9L(I)=ST(I)-ZP(3)*SDP(I)
      S9U(I)=ST(I)+ZP(3)*SDP(I)
      S8L(I)=ST(I)-ZP(4)*SDP(I)
      S8U(I)=ST(I)+ZP(4)*SDP(I)
250   CONTINUE
      DO 260 I=7,11
      J=12-I
      ST(I)=AMU+ZP(J)*SIGMA
      SDP(I)=DSQRT(VARMU+VARSIG*ZP(J)**2+2.D0*ZP(J)*COVAR)
      S9L(I)=ST(I)-ZP(3)*SDP(I)
      S9U(I)=ST(I)+ZP(3)*SDP(I)
      S8L(I)=ST(I)-ZP(4)*SDP(I)
      S8U(I)=ST(I)+ZP(4)*SDP(I)
260   CONTINUE
      IF(LG .EQ. 0)GO TO 280
      DO 270 I=1,11
      ST(I)=DEXP(ST(I))
      S9L(I)=DEXP(S9L(I))
      S9U(I)=DEXP(S9U(I))
      S8L(I)=DEXP(S8L(I))
      S8U(I)=DEXP(S8U(I))
270   CONTINUE
280   WRITE(6,204))(ST(I),S9L(I),S9U(I),S8L(I),S8U(I),I=1,11)
405   GO TO (410,420),ICODE
410   CALL ORDER(S,X,N)
      IF(LG .EQ. 1)GO TO 415
      WRITE(5,2045)
      WRITE(6,2055)
      WRITE(5,2065)(S(I),X(I),I=1,N)
      GO TO 3
415   WRITE(5,2075)
      CALL ORDER(STI,X,N)
      WRITE(6,2080)(STI(I),S(I),X(I),I=1,N)
      GO TO 3
420   DO 430 J=1,NN
      XM(J)=MX(J)
      XK(J)=K(J)
      RR(J)=XM(J)/XK(J)
430   CONTINUE
      IF(LG .EQ. 1)GO TO 435
      WRITE(6,2090)(SS(J),K(J),MX(J),RR(J),J=1,NN)
      GO TO 3
435   DO 440 J=1,NN
440   SSL(J)=DLOG(SS(J))
      WRITE(6,2095)
      WRITE(6,3000)(SS(J),SSL(J),K(J),MX(J),RR(J),J=1,NN)
```

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```
      GO TO 3
450   STOP
      END
      SUBROUTINE ORDER(A,B,N)
      DIMENSION A(1),B(1)
      DO 100 I=1,N
      K=N+1
      DO 100 J=1,K
      IF(A(J)-A(J+1))100,100,10
10    TEMP=A(J)
      A(J)=A(J+1)
      A(J+1)=TEMP
      TEMPP=B(J)
      B(J)=B(J+1)
      B(J+1)=TEMPP
100   CONTINUE
      RETURN
      END
      SUBROUTINE PROB(N,T,Z,P)
      DIMENSION T(1),Z(1),P(1),UPLIM(500),EST1(500),EST2(500),EST3(500),
     1EST4(500),EST5(500),EST6(500),SUM(500),POSP(500)
60    DO 130 I=1,N
      IF(DABS(T(I))-5.)64,64,61
61    IF(T(I))62,62,63
62    T(I)=-5.
      GO TO 64
63    T(I)=5.
64    CONTINUE
      CONST=.398942280401
      Z(I)=CONST*DEXP(-.5*T(I)*T(I))
      UPLIM(I)=DABS(T(I))
      EST1(I)=1.+.0498673470*UPLIM(I)
      EST2(I)=.0211410061*UPLIM(I)*UPLIM(I)
      EST3(I)=.0032776263*UPLIM(I)**3
      EST4(I)=.0000380036*UPLIM(I)**4
      EST5(I)=.0000488906*UPLIM(I)**5
      EST6(I)=.0000053383*UPLIM(I)**6
      SUM(I)=EST1(I)+EST2(I)+EST3(I)+EST4(I)+EST5(I)+EST6(I)
      POSP(I)=1.-.5*(1./SUM(I)**16)
      IF(T(I))110,120,120
110   P(I)=1.-POSP(I)
      GO TO 130
120   P(I)=POSP(I)
130   CONTINUE
      RETURN
      END
      LIST
E
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